1. INTRODUCTION

The gas permeability of concrete is a property which is recognized as a basic indicator of its durability. The measuring of air permeability used to mostly be carried out on samples, which were not exposed (before or during the tests) to certain external loads, which could cause microcracks in a hardened cement matrix. In the case of real structures there is always some stress level, and in this case the permeability of concrete is always affected by microcracks. To know both the permeability of plain concrete and the permeability of concrete containing a certain amount of microcracks is the basic assumption for a correct evaluation of its durability. There are different methods for measuring the parameters which characterize the permeability of concrete in relation to gas permeability [2], [3].

The distinctions are in the testing procedures as well as in the nature of the permeability parameters observed. In order to obtain a realistic view of the durability of a concrete structure, it is important to know the physical properties of its surface layers up to a depth of approx. 50 mm. The durability and the service life span of the structure depend on these properties. The execution procedures of concrete structures are accompanied by commonly known phenomena such as the “bleeding” of fresh concrete, the accumulation of cement milk in contact with the formwork (the wall effect), the method of the compaction of fresh concrete, the surface modifications of freshly poured concrete or possible aggregate segregation. As a consequence of these factors, the characteristics of fresh and hardened concrete are different near the formwork and in the mass of the concrete elements. This

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**P. PAULÍK, I. HUDOBA**

**THE INFLUENCE OF THE AMOUNT OF FIBRE REINFORCEMENT ON THE AIR PERMEABILITY OF HIGH PERFORMANCE CONCRETE**

**ABSTRACT**

The permeation of gases through hardened concrete is a physical property which is important to know, especially in terms of the defining properties of its surface layer. The gas permeability of the surface layer can fundamentally affect the serviceability limit state and the overall service life of certain types of concrete structures or elements such as containers for the storage of environmentally hazardous waste, concrete tunnel linings, concrete pavements, etc. To obtain reliable parameters characterizing the gas permeability of hardened concrete requires reliable test equipment and testing methods. At present, the most commonly used test equipment is a TORRENT PERMEABILITY TESTER (hereinafter referred as TPT), which was developed several years ago by the Swiss firm PROCEQ. This paper presents some air permeability test results carried out on high performance fibre-reinforced concrete specimens. The level of air permeability and some other physical properties of concrete were measured on concrete cube specimens with and without compressive stresses applied at a certain level during the test.

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**KEY WORDS**

- High performance concrete
- fibre reinforced concrete
- air permeability of hardened concrete specimens
- dynamic modulus of elasticity
- permeability of stressed concrete
is the main reason why it is necessary to assess the surface layers of hardened concrete structures by using non-destructive test equipment which guarantees fast and reliable test results. Such requirements can fulfil the TPT test method.

2. TPT MEASUREMENT DEVICE AND TESTING METHOD

The TPT measuring device consists of a vacuum pump, a two-chamber vacuum cell with sealing rings, a control unit and an automatic evaluation unit (Fig. 1). The principle of the device is based on measuring the time-dependent increasing of pressure in the inner chamber after a vacuum is generated by the pump. The outer chamber serves for the purpose of draining “fake” air flowing from the circumference of the head. By this means the direction of the air flowing into the inner chamber in a perpendicular direction to the vacuum cell plane is achieved (Fig.2). The advantage of TPT equipment is its portability, which easily allows measuring the permeability parameter of concrete surface layers directly at construction sites.

This set-up ensures the direct flow of air into the inner chamber and the calculation of the correct values of the permeability coefficient \( kT \). The calculations are based on a theoretical model expressed by the formula:

\[
kT = \left( \frac{V_c}{A} \right)^2 \frac{\mu}{2 \cdot \varepsilon \cdot P_a} \left( \frac{\ln \left( \frac{P_a + \Delta P}{P_a - \Delta P} \right)}{\sqrt{1} - \sqrt{\varepsilon}} \right)^2
\]

Where:
- \( kT \) – the coefficient of the permeability of the concrete [m²]
- \( V_c \) – the volume of the internal chamber [2.2 \cdot 10^{-6} m³]
- \( A \) – area of the inner chamber [19.6 \cdot 10^{-4} m²]
- \( \mu \) – viscosity of the air at 20 °C [1.84 \cdot 10^{-5} Ns/m²]
- \( \varepsilon \) – theoretical porosity of the concrete [0.15]
- \( P_a \) – atmospheric pressure [1000 Pa]
- \( \Delta P \) – change of the pressure in the inner chamber [measured value ... 20 N/m²]
- \( t_0 \) – the beginning of the measurement [60s]
- \( t \) – the total time of the measurement [max. 720s]

To obtain the values which characterize the permeability of a concrete surface layer by the TPT device, a measuring procedure is required, which consists of the following steps:
- The surface of the concrete should be cleaned of dust at the place of measurement
- The control unit of the touchscreen is switched on, and the two chamber vacuum cell is attached to the place of measurement.
- By opening the valve, the air is sucked off the outside chamber so that an under-pressure of 1 bar is created, and the cell leaches to the concrete surface with its sealing ring.
- The procedure is followed by opening the valve on the inlet hosepipe which is connected to the inner chamber; consequently a vacuum is created in this chamber by the pump.
- The measurement is terminated automatically, indicating the value of the coefficient of permeability \( kT \) [m²] and the depth of vacuum penetration \( L \) [mm] on the screen. The parameters are recorded immediately when an effective increase in the under-pressure reaches the calibrated pressure difference, which is more than 20 mbar, respectively after 720 seconds.
- The \( kT \) and \( L \) parameter measurements, in situ, are obtained in less than 15 minutes.

The measured permeability values, \( kT \) and the depth of vacuum penetration \( L \), depend on the moisture of the surface layer of the concrete. By increasing the moisture of the concrete the measured value of the permeability factor \( kT \) decreases. As part of the TPT measuring device there is also a sensor for measuring the moisture...
content of the concrete’s surface layer by using electrical resistance $\rho$. The permeability coefficient $kT$, for wet or young concrete, is determined by the correction of the $kT$. For this purpose a nomogram for determination of the electrical resistance $\rho$ value can be used. The nomogram was developed by the TPT equipment manufacturer [5]. The overall evaluation of the permeability measurements of the surface layers of the concrete by using the permeability factor $kT$ and the depth of vacuum penetration $L$ is accomplished by classification of the surface layer into a quality class according to Tab. 1.

During practical permeability parameters measurements performed on the construction, the manufacturer of the TPT measuring equipment requires compliance with the following principles:

- The measurement point:
  - not to carry out measurements on wet concrete.
  - The concrete surface must be sufficiently flat at the measurement location in order to enable the leeching effect of the vacuum head
- The surface of the concrete should not be cracked
- The distance between the outer edge of the structural element and the external diameter of the cell must be a min. of 20 mm
- The inner chamber of the cell should not be located above the reinforcement bar

- The manufacturer of the TPT equipment recommends regular calibrations, especially in cases of higher pressures and temperatures
- While measuring electrical resistance on wet concrete, it is optimally recommended to provide 6, but at least 3, measurements.
- To determine the $kT$ value it is essential to use the average value of the measured electrical resistance $\rho$ and the measured $kT$ value deducted from the graph, which was developed by the TPT equipment manufacturer
- The thickness of the concrete element in the location of the measurement must be greater than the depth of vacuum penetration $L$.

### Tab. 1 Quality classes of the concrete’s surface layer

<table>
<thead>
<tr>
<th>Quality of the surface layer of the concrete</th>
<th>Index</th>
<th>$kT.10^{16}$ (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>very bad</td>
<td>5</td>
<td>&gt;10</td>
</tr>
<tr>
<td>bad</td>
<td>4</td>
<td>1.0 ± 1.0</td>
</tr>
<tr>
<td>normal</td>
<td>3</td>
<td>0.1 ± 1.0</td>
</tr>
<tr>
<td>good</td>
<td>2</td>
<td>0.01 ± 0.1</td>
</tr>
<tr>
<td>very good</td>
<td>1</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

### 3. AIR PERMEABILITY OF PLAIN CONCRETE SPECIMENS EXPOSED TO COMPRESSIVE STRESS

The TPT equipment is most commonly used for testing the air permeability of surface layers on reinforced or prestressed concrete structures. During the service life of these structures there is a certain state of stress in its surface layers at different places, which is dependent on the position and magnitude of the loads at that moment. There is relatively little experience with the measurements of gas permeability through high-strength fibre-reinforced concrete. For example, PICADENT, V., et al. [2] measured gas permeability on normal, high performance and fibre-reinforced concrete samples, which were cut from cylinders (110 mm and 220 mm in diameter) and then exposed to cyclical pressures with a magnitude reaching 60% and 90% of the ultimate compressive strength. The impact of the stress level on gas permeability was monitored on unloaded samples perpendicular to the cross section. ADÁMEK, J., et al. [1] monitored the changes of the permeability coefficient $kT$ over time (by the TPT method) on normal strength concrete, using several types of drainage foils attached to the shuttering.

The tests presented were focused on monitoring the air permeability (by using the TPT method) on high-performance concrete specimens, with and without different amounts of fiber reinforcement exposed to different stress levels. Measurements were provided on concrete
cubes in a direction perpendicular to the direction of the casting and inducing pressure forces (Fig. 4b). Cubes with an edge of 200 mm were used for the tests in accordance with the requirements for the TPT method [5]. All the cubes were made of high-performance concrete (type B) and high-performance fibre-reinforced concretes (types A and C). The specimens were stored over a time span of 10 years in free air in a laboratory environment. FIBRAFLEX metal fibres (French origin) were used as fibre reinforcements. The basic parameters of the compressive strength and dynamic modulus of elasticity of the concrete cubes tested are in Tabs. 2 and 3. The amount of fibre reinforcement means its weight fraction in the whole mix.

The mean values of the air permeability coefficient $k_T$ and the depth of vacuum penetration $L$ on the concrete samples measured on different types of concrete A, B and C under different compressive stress levels are presented in Tab. 4. Particular measurements were carried out at compressive stress levels equal to 0%, 30% and 60% of the mean compressive strength of the concrete at the actual time, expressed by the $f_{cm}$/$f_{cm}$ ratio. Permeability was also measured after unloading on each sample (from the 30% and 60% of $f_{cm}$ stress level), but these values are not presented in this paper. After the measurement of air permeability $k_T$ and the depth of vacuum penetration $L$ were done, measuring the dynamic modulus of elasticity $E_{c,dyn}$ was carried out using an ultrasound device. The values of the dynamic modulus of elasticity given are in Table 5 for each type of concrete (A, B and C) at different compression stress levels. On each sample 3 measurements were carried out along its diagonal, and then the average value was computed.

The effect of the amount of fibre reinforcement on the change in permeability coefficient $k_T$ depending on the external compressive stress level is expressed by the values presented in Tabs. 6, 7 and 8. The measured changes in the permeability values are possible to express by the relative values presented in Tabs. 9 and 10. A graphic presentation of the air permeability coefficient $k_T$ increasing (vs. decreasing) depending on the amount of fibre-reinforcement and compressive stress level is shown in Figs. 5, 6 and 7.

**Tab. 2 Compressive strength of concrete (mean values)**

<table>
<thead>
<tr>
<th>Type of concrete</th>
<th>Amount of fibre reinforcement [%]</th>
<th>Compressive strength $f_{cm,cube200}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>age: 28 days</td>
</tr>
<tr>
<td>A</td>
<td>1.37</td>
<td>60.63</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>50.98</td>
</tr>
<tr>
<td>C</td>
<td>2.74</td>
<td>51.85</td>
</tr>
</tbody>
</table>

**Fig. 4 Air permeability measurements on concrete cube specimens**
a) Air permeability test on unloaded cube specimens, b) Air permeability test on cube specimens exposed to a compressive load

**Tab. 3 Dynamic modulus of elasticity (mean values)**

<table>
<thead>
<tr>
<th>Type of concrete</th>
<th>Amount of fibre reinforcement [%]</th>
<th>Dynamic modulus of elasticity $E_{c,dyn}$ [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>age: 28 days</td>
</tr>
<tr>
<td>A</td>
<td>1.37</td>
<td>41.49</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>41.78</td>
</tr>
<tr>
<td>C</td>
<td>2.74</td>
<td>43.63</td>
</tr>
</tbody>
</table>

**Tab. 4 Values of air permeability coefficient $k_T$ and the depth of vacuum penetration $L$ (mean values)**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Unloaded</th>
<th>Stress level 30% $f_{cm}$</th>
<th>Stress level 60% $f_{cm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_T 10^{-16}$</td>
<td>$L$ [mm]</td>
<td>$k_T 10^{-16}$</td>
</tr>
<tr>
<td>C1</td>
<td>0.287</td>
<td>0.371</td>
<td>36.8</td>
</tr>
<tr>
<td>C3</td>
<td>0.454</td>
<td>0.371</td>
<td>44.3</td>
</tr>
<tr>
<td>B1</td>
<td>0.303</td>
<td>0.321</td>
<td>37.8</td>
</tr>
<tr>
<td>B2</td>
<td>0.338</td>
<td>0.321</td>
<td>39.9</td>
</tr>
<tr>
<td>A4</td>
<td>1.098</td>
<td>1.159</td>
<td>53.1</td>
</tr>
<tr>
<td>A1</td>
<td>1.220</td>
<td>1.159</td>
<td>53.6</td>
</tr>
</tbody>
</table>

* these values are not included in the mean value because of the occurrence of a crack, which significantly affected the test result.
Tab. 5 Dynamic modulus of elasticity $E_{c,dyn}$ (mean values)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stress level 30% $f_{cm}$</th>
<th>Stress level 50% $f_{cm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>measurement number</td>
<td>$E_{c,dyn}$ [GPa]</td>
</tr>
<tr>
<td>C1</td>
<td>1</td>
<td>51.3</td>
</tr>
<tr>
<td>C3</td>
<td>1</td>
<td>46.6</td>
</tr>
<tr>
<td>B1</td>
<td>1</td>
<td>43.9</td>
</tr>
<tr>
<td>B2</td>
<td>1</td>
<td>44.4</td>
</tr>
<tr>
<td>A4</td>
<td>1</td>
<td>46.4</td>
</tr>
<tr>
<td>A1</td>
<td>1</td>
<td>47.3</td>
</tr>
</tbody>
</table>

Tab. 6 The effect of the amount of fibre reinforcement on permeability coefficient $k_T$ at different levels of compressive stress (from level of 30% to 60% of $f_{cm}$)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stress level 30%</th>
<th>Stress level 60%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$kT \cdot 10^{-18}$ [m$^3$] mean</td>
<td>$kT \cdot 10^{-18}$ [m$^3$] mean</td>
</tr>
<tr>
<td>C1</td>
<td>2.645</td>
<td>1.139</td>
</tr>
<tr>
<td>C3</td>
<td>0.616</td>
<td>2.464</td>
</tr>
<tr>
<td>B1</td>
<td>0.299</td>
<td>8.326</td>
</tr>
<tr>
<td>B2</td>
<td>0.341</td>
<td>6.731</td>
</tr>
<tr>
<td>A4</td>
<td>1.495</td>
<td>17.650</td>
</tr>
<tr>
<td>A1</td>
<td>2.151</td>
<td>17.650</td>
</tr>
</tbody>
</table>

* - these values are not included in the average value because of the occurrence of cracks, which significantly affected the test results

Tab. 7 The effect of the amount of fibre reinforcement on the permeability coefficient $k_T$ after unloading from 60% of $f_{cm}$ stress level (in comparison to the permeability measured after unloading from 30% of $f_{cm}$ stress level)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stress level 30%</th>
<th>Stress level 60%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$kT \cdot 10^{-18}$ [m$^3$] mean</td>
<td>$kT \cdot 10^{-18}$ [m$^3$] mean</td>
</tr>
<tr>
<td>C1</td>
<td>0.426</td>
<td>0.380</td>
</tr>
<tr>
<td>C3</td>
<td>0.334</td>
<td>0.380</td>
</tr>
<tr>
<td>B1</td>
<td>0.179</td>
<td>0.213</td>
</tr>
<tr>
<td>B2</td>
<td>0.246</td>
<td>0.359</td>
</tr>
<tr>
<td>A4</td>
<td>1.065</td>
<td>2.829</td>
</tr>
<tr>
<td>A1</td>
<td>1.654</td>
<td>3.044</td>
</tr>
</tbody>
</table>

Tab. 9 Relative increase of permeability

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stress level (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
</tr>
</tbody>
</table>

Tab. 10 Relative increase of permeability after at 30 and 60% of $f_{cm}$ unloading from 30 and 60% of $f_{cm}$

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stress level (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
</tr>
</tbody>
</table>

Fig. 5 Relation between an increase in relative permeability (compressive stress level increasing from 30% to 60% of $f_{cm}$) and the amount of fibre reinforcement.

Fig. 6 Relative increase in permeability at 30% and 60% of $f_{cm}$ stress level
between the dynamic modulus of elasticity and the amount of fibre-reinforcement is shown in Fig. 8 (the values are at a stress level equal to 30% of $f_{cm}$).

### 4. CONCLUSIONS

In relation to the increasing amount of fibres in concrete, there is a significant reduction of its permeability under a compressive load. As more fibres are used in concrete, the permeability affected by the increased load is lower. Concrete without fibers presents a more than 23-times greater degree of permeability after the stress level was increased from 30 to 60% of $f_{cm}$. The same concrete with a fiber amount of 2.74% showed only a 4-times greater degree of permeability after increasing the same load.

The quality of the compaction of a concrete mix has a much greater impact on permeability than the amount of fibre reinforcement. While increasing the compressive load level, a crack occurred in some specimens. This fact strongly influenced the test results. If a visible crack developed (at a stress level of 30% or 60% of $f_{cm}$), this result was not used for calculating the test results. After discharging the compressive load, the crack was closed and was not visible to the eye.

From the measurement results, we concluded that the permeability measured at a surface disturbed with a visible crack cannot be used in evaluating the results.

After discharging the compressive load, the regeneration of the permeability was more effective on concrete specimens without fiber reinforcement, where the permeability decreased more than 8 times. On the other hand, concrete with a fibre content of 2.74% regenerated only 2.4 times. In concrete specimens without fiber reinforcement, a reduction in relative permeability (0.66 times) was observed at the 30% of $f_{cm}$ stress level. In the case of fibre reinforced concrete this phenomenon does not occur and the permeability of the concrete specimens at stress level of 30% of $f_{cm}$ was approximately the same as the permeability of the unloaded concrete specimens.

The impact of the amount of fiber reinforcement was also observed on the permeability of the concrete specimens after unloading. The specimens without fibers, which were loaded to a stress level of 60% of $f_{cm}$ and consequently unloaded, showed a 4.3 times increase in permeability in comparison with the state after unloading from a stress level of 30% of $f_{cm}$. On the other hand, the same concrete containing 2.74% fibers, showed in the same case only a 2.4 times increase in permeability.

The dynamic modulus of elasticity is influenced by the compressive stress level as well as by the amount of fiber reinforcement. When the stress level was increased to 60% of $f_{cm}$, the dynamic modulus of elasticity was also increased (1.1 times in the specimens with 2.74% of fiber reinforcement and 1.06 times in the specimens without fiber reinforcement). The dynamic modulus of elasticity at the stress level of 30% of $f_{cm}$ was higher in specimens with fibre reinforcement (the higher amount of fiber reinforcement induced higher values

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stress level, 30% $f_{cm}$</th>
<th>Stress level, 60% $f_{cm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>48.6 $E_{c,dyn}$ (GPa)</td>
<td>53.4 $E_{c,dyn}$ (GPa)</td>
</tr>
<tr>
<td>C2</td>
<td>47.2 $E_{c,dyn}$ (GPa)</td>
<td>53.1 $E_{c,dyn}$ (GPa)</td>
</tr>
<tr>
<td>A4</td>
<td>46.7 $E_{c,dyn}$ (GPa)</td>
<td>50.3 $E_{c,dyn}$ (GPa)</td>
</tr>
<tr>
<td>A1</td>
<td>48.2 $E_{c,dyn}$ (GPa)</td>
<td>50.8 $E_{c,dyn}$ (GPa)</td>
</tr>
</tbody>
</table>

**Tab. 11 Effect of the amount of fibre reinforcement on the dynamic modulus of elasticity $E_{c,dyn}$ at 30 and 60% of $f_{cm}$ stress level**
of the dynamic modulus of elasticity). After unloading from a certain compressive stress level, the dynamic modulus of elasticity remained at the same level as before the unloading. On a stress level of 60% of $f_{cm}$, the measured values of the dynamic modulus of elasticity were higher at the middle part of the specimen (cube) than at the edges (the difference between the measured values was approx. 15%).

REFERENCES


This paper was realized with the support of the VEGA research project No. 01/0180/08 - Factors influencing the properties of the surface layers of concrete structural elements from the points of view of execution and environmental action.